Injection-Locked Dual Opto-Electronic Oscillator With Ultra-Low Phase Noise and Ultra-Low Spurious Level

Weimin Zhou, *Member, IEEE,* and Gregory Blasche

***Abstract*—We report a new injection-locked dual opto-electronic oscillator (OEO) that uses a long optical fiber loop master oscillator to injection lock into a short-loop signal-mode slave oscillator, which showed substantial improvements in reducing the phase noise and spurs compared to current state-of-the-art multiloop OEOs operating at 10 GHz. Preliminary phase-noise measurement indicated approximately 140-dB reduction of the spurious level.**

***Index Terms*—Injection locked, opto-electronic oscillator (OEO), phase noise, spurious level.**

I. Introduction

HIGH-PERFORMANCE microwave oscillators require a high quality factor (Q) cavity in order to reduce the phase noise. However, the Q is limited in traditional microwave electronic devices due to size and power constraints. In 1995, an opto-electronic oscillator (OEO) was introduced by Yao and Maleki [1], [2], which used a long optical fiber as a delay line in a feedback loop completed both by optical and electronic paths, as shown in Fig. 1. The basic concept is to convert the microwave oscillations into modulated laser light that is sent into a long optical fiber. A photodetector converts the modulated light signal back into microwave signals that are amplified and filtered by a microwave filter, which is then fed into the optical modulator closing the feedback loop. Several kilometers of low-loss optical fiber in the OEO loop can generate a cavity with Q values more than 10^9, which is several orders of magnitude higher than that from the best commercial microwave filters. In the OEO, the mode spacing is inversely proportional to the cavity Q. Therefore, the RF filter is not able to filter out many of the unwanted modes, especially those close to the carrier.

Multiloop OEOs were recently reported [3]–[5], which suppress the spurs by adding a second loop in the cavity. As shown in Fig. 2, the modulated laser light is split into two optical fibers, a long fiber and a short one. Two photodetectors convert the light signals into separate microwave signals that are combined using a microwave power combiner. The combined signal is sent to the RF filter, amplifier, and fed back to the optical modulator. Using

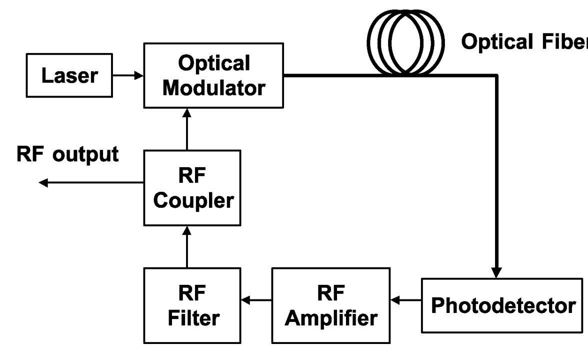

Fig. 1. Block diagram of the OEO.

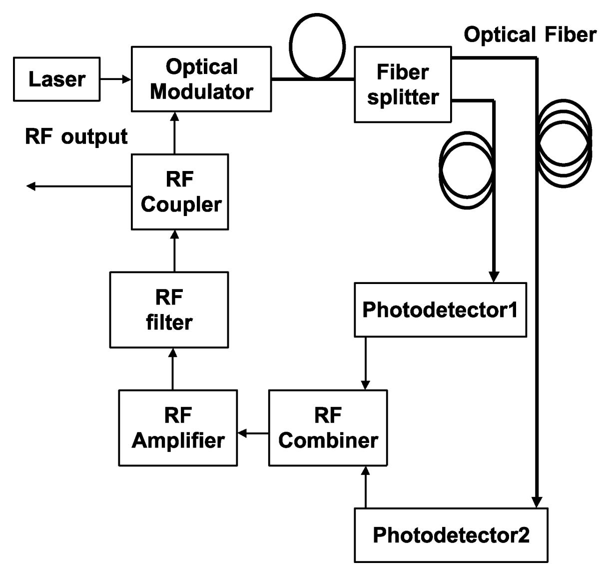

Fig. 2. Block diagram of the dual-loop OEO.

the Vernier caliper effect, one can use an RF phase shifter to tune one mode from the short loop close to a mode from the long loop within the filter band. This combined mode will be enhanced in the oscillator, forming a strong mode, which becomes the carrier signal. Due to the energy competing effect, all the other mismatched modes will be suppressed. A 30-dB reduction of the spurious level has been reported [5] using this scheme. However, the spurious modes are still supported by either the long- or short-loop cavity, making it hard to further reduce the spurious level. In addition, this parallel dual-loop OEO sacrifices the high Q produced from the long fiber. The overall Q is “averaged” between the long loop’s high Q and the short loop’s low Q

Manuscript received March 31, 2004; revised July 9, 2004. The work of G. Blasche was supported by the Army Research Laboratory (ARL) under ARL Cooperative Agreement DAAD19-00-2-004.

W. Zhou is with the Sensors and Electron Devices Directorate, U.S. Army Research Laboratory, Adelphi, MD 20783 USA (e-mail: wzhou@arl.army.mil).
G. Blasche is with the Physics Department, Boston University, Boston, MA 02215 USA (e-mail: gblasche@alum.bu.edu).

Digital Object Identifier 10.1109/TMTT.2004.842489

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAR 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Injection-Locked Dual Opto-Electronic Oscillator With Ultra-Low Phase Noise and Ultra-Low Spurious Level**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Boston University,Department of Physics,Boston,MA,02215**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We report a new injection-locked dual opto-electronic oscillator (OEO) that uses a long optical fiber loop master oscillator to injection lock into a short-loop signal-mode slave oscillator, which showed substantial improvements in reducing the phase noise and spurs compared to current state-of-the-art multiloop OEOs operating at 10 GHz. Preliminary phase-noise measurement indicated approximately 140-dB reduction of the spurious level.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

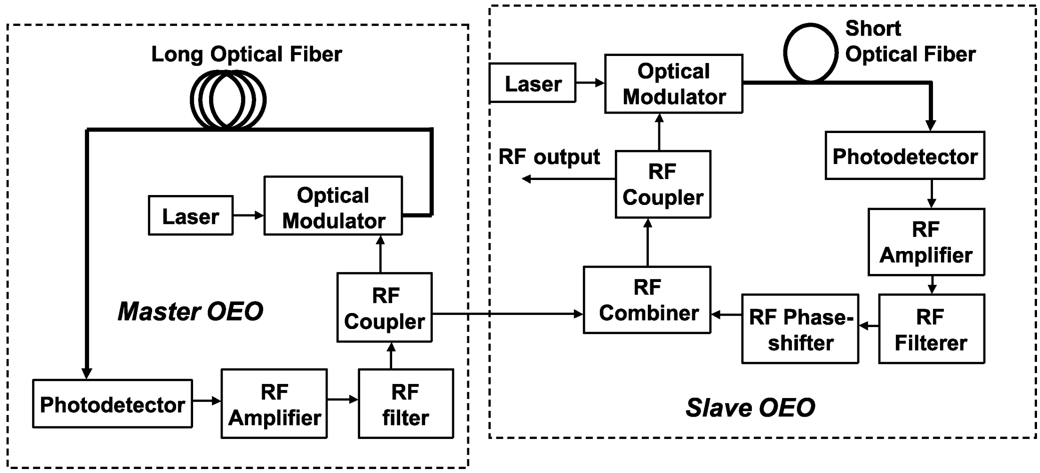

Fig. 3. Block diagram of an injection-locked dual OEO.

so that the phase noise increases compared with the single-loop long-fiber OEO. As shown in [5], the phase-noise level of a double-loop OEO with 8.4- and 2.2-km fibers is only equivalent to that from a 4.4-km fiber single-loop OEO.

II. Experimental Results

A. Injection-Locked Dual OEO

To solve the problem of maintaining the high Q of the multiloop system while eliminating the spurious modes that are supported by the cavity loops, we introduce a new injection-locked dual OEO scheme. Injection-locking schemes have been used and studied previously in nonoptical RF oscillators [6], [7], which demonstrated an improvement in phase-noise reduction for their low-Q slave oscillators. Here, in our OEO, we use the injection scheme differently where the slave OEO is used to filter out the multimode spurs generated by the high-Q master OEO and to maintain the high Q by the injection locking. As shown in Fig. 3, the RF output signal from a high-Q long-fiber single-loop master OEO is injected into a short fiber slave OEO to lock in the oscillation frequency and phase. The length of the slave OEO's optical fiber is chosen such that only one mode is allowed within the RF-filter bandwidth in that single loop OEO, therefore, suppressing the spurious modes from the master OEO by the destructive interference in the slave OEO's cavity. Thus, the master OEO's long fiber builds the high Q and the slave OEO's short-loop filter out the spurs.

To make a proof-of-principle demonstration, we built a master OEO using greater than 6 km of Corning SMF28 optical fiber having an effective index of refraction n of $\sim$1.46 at 1550 nm, which is the wavelength of the single-mode laser used to carry the signal in the optical path. In the first approximation, the frequency spacing of the modes is $\Delta f \sim \mathrm{c}/n\mathrm{L}$, where c is the speed of light and L is the fiber length. Therefore, Δf in the master oscillator is approximately 34 kHz. The RF filter used in the master OEO has a center frequency at 10 GHz and a filter bandwidth of 8 MHz, allowing hundreds of modes to oscillate in the master OEO. Fig. 4(a) shows the spectrum of the master OEO measured using an Advantest-3271A microwave spectrum analyzer, which indicates a 34.8-kHz spacing between each oscillation peak. The envelope shape of the multimode amplitudes reflects the passband characteristic of the multisection RF filter. Fig. 4(b) shows the single peak mode spectrum of

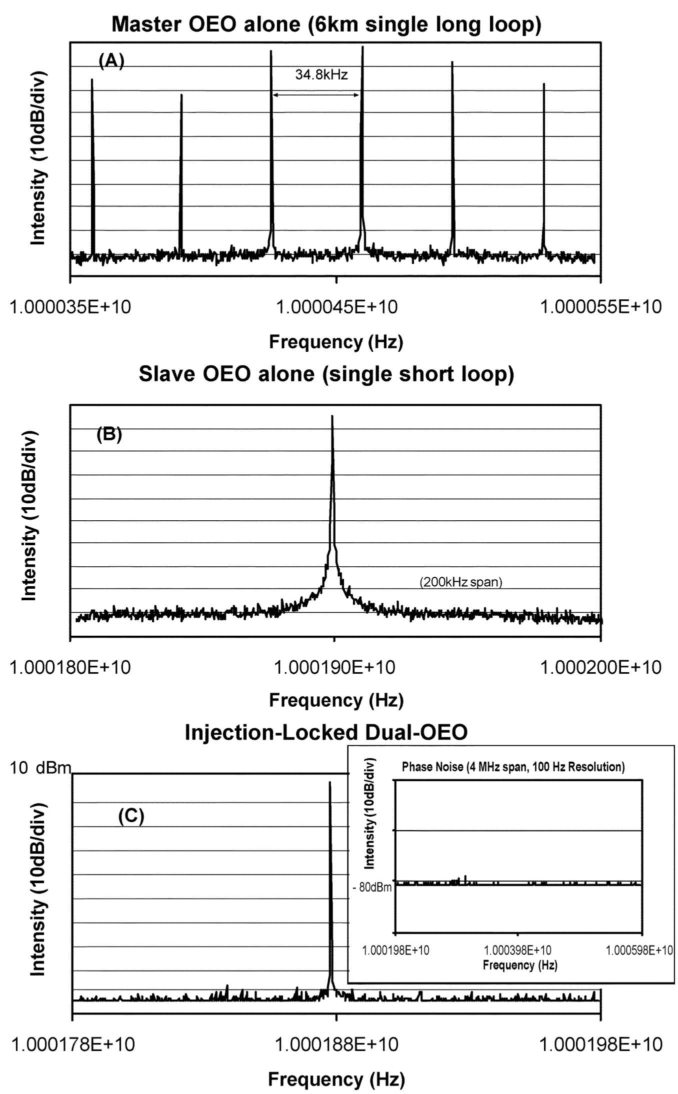

Fig. 4. Experimental data for the oscillator output taken from a RF spectrum analyzer for the: (a) master OEO alone, (b) slave OEO alone, and (c) injection-locked OEO. (Spectra (a)–(c) are taken with the same span, resolution, and reference level.)

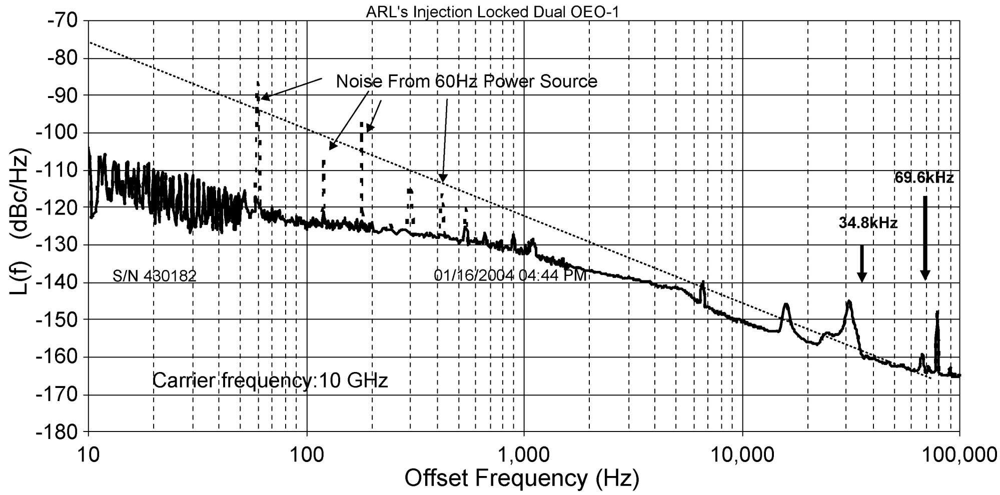

Fig. 5. Phase-noise measurement data of the injection-locked dual OEO, which shows the relative phase-noise intensity versus offset frequency from the 10-GHz center carrier. 60-Hz noise from the power supply is denoted by a dashed line for clarity. The doted line indicates a range of a worst uncompressed noise level.

the slave OEO (composed of a ~50-m optical fiber length) free running without injection lock, which has a broader linewidth compared to the peaks of the master loop shown in Fig. 4(a). After the multimode signals of the master OEO are injected into the slave OEO, an RF phase shifter is used to bring the slave OEO's oscillation into the locking range with one of the strong modes of the master OEO. When locked, the side modes are drastically reduced. Fine tuning of the slave loop phase makes the multimode spurs disappear from the measured RF spectrum, as shown in Fig. 4(c). We use the same settings, 200-kHz span, 10-dBm reference level, and 10-Hz resolution bandwidth, for all three measurements. The single peak signal after the injection locking becomes sharp and clean. The spurs at multiples of 34.8 kHz disappear from the output. A 4-MHz span continuation spectrum is inserted into Fig. 4(c) to show no other spurs within the RF filter bandpass. (Since the spurs are symmetric with respect to the center peak frequency, we only need to show the spectrum from the center peak to the higher frequency end of the filter.) The inserted spectrum was taken separately because different resolution bandwidth has to be used for the longer span. The noise floor after injection lock, shown in Fig. 4(c), is even lower than that from the master OEO [see Fig. 4(a)]. Notice that the noise level of the RF spectrum analyzer is much higher than that from our OEO, therefore, a more sophisticated phase-noise measurement system is required in order to measure the true phase noise of the OEO.

B. Phase-Noise Measurement

A preliminary phase-noise measurement has been performed using a precision phase measurement technique developed at the National Institute of Standards and Technology (NIST), Boulder, CO [8]–[10]. The phase-noise measurement equipment is commercially provided by Femtosecond System Inc., Denver, CO, which is capable of dual-channel cross-correlation measurements [11]. However, due to the unavailability of two identical RF reference sources at this time, we have performed a noise measurement using a two-source single-channel method. For this measurement, a reference source is frequency/phase locked to the OEO under test. Phase noise is detected after the carrier signal is canceled at a mixer by tuning the reference into the opposite phase. The measured phase noise represents the highest noise of the two oscillators. We have used another double-loop OEO with effective 4 km of fiber length as the reference source. As explained in Section II-A, when the reference OEO is locked by our high-Q OEO under test, the phase noise from the reference OEO could be lower than that when it is free running. However, spurs from the reference OEO will remain in this case.

In Fig. 5, we show the preliminary measured phase-noise data. There are a few peaks expressed by dashed lines, which are associated with the 60-Hz ac power sources used on all the voltage supplies of our OEO. We verified from the raw data that the frequencies of these peaks are exact multiples of 60 Hz. We believe that if we replace our voltage sources for the photodetectors and optical modulators with batteries, we can eliminate those peaks from the noise spectrum. The periodic noise oscillation below 60 Hz was present in a noise floor measurement taken without the OEO under test. We also know that if we have any spurs, they must be located at 34.8 and 69.6 kHz in our phase-noise spectrum. We can see some small peaks that may be associated with the spurs, but their intensity level is well below -140 dBc/Hz, which is much lower than the spur level reported from the double-loop OEO scheme in [4] and [5]. The first one or two spurs closest to the carrier should be the strongest. Since the slave OEO's short cavity allows only single-mode oscillation, when the phase shifter is tuned to lock the oscillation to center frequency, the other spur modes will be out-of-phase, the further from the center frequency, the more the phase mismatch will be. Secondly, the RF filter profile will also reduce the magnitude of any mode away from the center frequency. This result shows that our spur reduction concept of using destructive interference of the unsupported spur modes in the short slave OEO cavity provides greater reduction of the spurious modes than the double-loop OEO configuration, which uses energy competition between the supported spur modes and selected carrier mode. The preliminary noise data also indicates a low phase-noise level below -110 dBc/Hz at a low offset frequency (10–100 Hz). This data demonstrates that the high Q

from our master OEO is preserved in the slave OEO after the injection locking. However, the frequency tuning of our reference oscillator is somewhat difficult due to the poor design of the tuning mechanism. This makes phase locking difficult using a low-gain phase-locked loop. Therefore, noise compression is possible at the low offset-frequency range due to the relative high gain of the phase-locked loop. To be safe in the interpretation of the data, we have drawn a straight dotted line denoting the upper range in the noise spectrum, under which we believe the real noise level should be. The injection-locked OEO was laid out on an optical table during the measurement in an environmental controlled laboratory, therefore, thermal instability is thought to be at a minimum.

III. Discussions

A. Injection-Locking Conditions

Different physical states of the injection-locked OEO have been observed during the inject-locking process under different conditions. The phase-noise level and spurious level may change depending on the relative RF signal power level injected into the slave OEO with respected to the slave OEO's free-running power level. When the spur level of the injected signal from the master OEO matches that from the same spur after one cycle feedback in the slave OEO, destructive interference may work the best to cancel the spur. We have also noticed that, when the frequency of the free-running slave OEO is tuned at the exact frequency of one of the master OEO's modes, after the injection lock, the oscillation frequency may hop to another neighboring mode. Only after additional fine tuning of the phase shifter, will we observe a certain drop of spur level and noise level. This hints that there may be a self-cleaning process occurring under certain injection-locking conditions. Additional investigation and theoretical studies are needed to confirm this.

B. Comparison

The major architectural difference from the previous multiloop OEO is that the resonant cavity of the long loop of the master OEO is isolated and independent from the cavity in the slave OEO so there is no feedback for the spurious modes. This will make a fundamental difference in the physics for the oscillation signal created in the injection-locked dual OEO. First, unlike the multiloop OEO, which is in a parallel configuration having an "average" Q, the injection-locked dual OEO is in a series configuration. It has been demonstrated [6], [7] that the phase noise of a low-Q microwave oscillator can be reduced by injection locking from a high-Q source. Therefore, we believe that, at the injection-locked condition, the high Q of the master OEO is preserved in the slave OEO. Secondly, since the slave OEO cavity is designed to allow only single-mode oscillation, once the phase shifter is tuned such that the slave OEO's mode is matched to one of the master OEO's modes for injection locking, the super-mode spurs (within the RF filter band) from the master OEO that are injected into the slave OEO cannot be supported by the slave OEO's short-loop oscillator cavity. Therefore, these spurious modes will die out due to the destructive interference within the short loop. This has a better result compared with the multiloop OEO in which their interlinked multiloop cavity still supports the spur modes.

We can also compare our injection-locked OEO with many conventional microwave oscillators. With the high Q, our OEO phase noise compared favorably with the best nonoptoelectronic commercial microwave oscillators in the low offset-frequency range (up to 600 Hz, indicated by the preliminary data). Since the low offset-frequency phase noise is dominate by the oscillator's Q value, in the large offset-frequency range, the OEO noise figure is slightly worse than the best commercial oscillator. Since we have not yet focused on lowering the noise floor of the electronic circuitry in this project, and the higher offset-frequency noise is attributed to the electronics, we believe that it is a solvable engineering problem to further reduce the noise figure in the higher offset-frequency range by improvement of the electronics. Besides the phase-noise comparison, the OEO technology has a major advantage over conventional microwave oscillators by offering great frequency agility over a very wide operating range. This is due to the fact that even a large change in microwave frequencies represents a very small fractional bandwidth when compared to the optical carrier frequency.

IV. Conclusions

In conclusion, we have developed an injection-locked dual-OEO architecture, which maintains the high Q produced by a long fiber loop master OEO and uses a short-loop slave OEO to filter out the spurs produced by the master OEO so that the oscillator output has ultra-low phase noise and an ultra-low spurious level. This oscillator can be built using commercially available opto-electronic and microwave components at a reasonably low cost.

Acknowledgment

The authors wish to thank Dr. C. Fazi for providing his leadership and support for the Frequency Control Program at the U.S. Army Research Laboratory (ARL), Adelphia, MD, as well as his many helpful technical discussions. The authors also thank Dr. W. Walls, Femtosecond System Inc., Denver, CO, for his assistance with phase-noise measurement and training. Author G. Blasche would also like to thank Dr. B. Goldberg, Boston University Photonics Center, Boston, MA.

References

[1] X. S. Yao and L. Maleki, "Converting light into spectrally pure microwave oscillation," *Opt. Lett.*, vol. 21, pp. 483–485, Apr. 1996.

[2] ——, "Optoelectronic microwave oscillator," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 13, no. 8, pp. 1725–1735, Aug. 1996.

[3] ——, "Dual microwave and optical oscillator," *Opt. Lett.*, vol. 22, no. 24, pp. 1867–1869, Dec. 1997.

[4] ——, "Multi-loop optoelectronic oscillator," *IEEE J. Quantum Electron.*, vol. 36, no. 1, pp. 79–84, Jan. 2000.

[5] D. Eliyahu and L. Maleki, "Low phase noise and spurious level in multiloop optoelectronic oscillator," in *Proc. IEEE Int. Frequency Control Symp.*, 2003, p. 405.

[6] H.-C. Chang, X. Cao, M. J. Vaughan, U. K. Mishra, and R. A. York, "Phase noise in externally injection-locked oscillator array," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 11, pp. 2035–2041, Nov. 1997.

[7] K. Kurokawa, "Injection locking of microwave solid-state oscillator," *Proc. IEEE*, vol. 61, no. 10, pp. 1386–1410, Oct. 1973.

[8] *Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology—Random Instabilities*, IEEE Standard 1139-1999, 1999.

[9] D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls, Eds., "Characterization of clocks and oscillators," NIST, Boulder, CO, Tech. Note 1337, Mar. 1990.

[10] D. A. Howe, D. W. Allan, and J. A. Barnes, "Properties of signal sources and measurement methods," in *Proc. 35th Annu. Frequency Control Symp.*, 1981, pp. A1–A47.
[11] W. F. Walls, "Cross-correlation phase noise measurements," in *Proc. IEEE Frequency Control Symp.*, 1992, pp. 257–261.

Weimin Zhou (M'04) received the B.S. and M.S. degrees in physics from the Universite de Toulouse, Toulouse, France, in 1982 and 1983, respectively, and the Ph.D. degree in physics from Northeastern University, Boston, MA, in 1991.

He is currently a Research Physicist and Team Leader with the U.S. Army Research Laboratory, Adelphi, MD. His team is involved with the design and fabrication of novel opto-electronic devices, opto-electronic integrated circuits, and development of RF microwave-photonic devices and systems including RF-photonic oscillators and optical-controlled phased-array antennas.

Dr. Zhou was the recipient of a National Research Council Research Associateship Award (1991–1994) while with the U.S. Army Electronic Technology and Devices Laboratory, Fort Monmouth, NJ.

Gregory Blasche received the B.A., M.A., and Ph.D. degrees in physics from Boston University, Boston, MA, in 1999, 2001, and 2004, respectively. His doctoral research involved the development of a high-power line-narrowed laser diode array for the generation of hyperpolarized noble gases.

He is currently with the Physics Department, Boston University, Boston, MA.